Fatigue Characterization of Functionalized Carbon Nanotube Reinforced Carbon Fiber Composites

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Abstract

The primary purpose of this analytical report is to compare tension-tension fatiguing of a carbon fiber composite to tension-compression fatiguing. Although carbon fiber composites hold up well in tension-tension fatiguing, there is little knowledge of the effects of tension-compression cyclic testing, especially in the higher regimes. The composites were fabricated using the vacuum assisted resin transfer molding method, VARTM, and are composed of IM7 four harness satin weave carbon fiber (54% by volume) and Epon 862 with curing agent W (46% by volume). The current research shows that carbon fiber composites are resistant to tension-tension fatiguing. However, when the composite must also endure compressive forces the fatigue life is considerably shorter. The results show that at R-ratios, maximum stress over minimum stress, of 0.1 & -0.1 tension-compression fatiguing will result in a failure three times earlier then tension-tension fatiguing for the same maximum stress value. Microscopy shows the extreme damage that carbon fiber epoxy composites endure during tension-compression fatiguing.

1. Introduction

As designers push for increased performance, there is an evident need for advanced multi-functional materials. Carbon fiber composites are of particular interest for the automotive and aerospace industries for their high strength, lightweight, and high stiffness. These characteristics make carbon fiber composites one of the most advanced materials to date. However, it does have a few significant drawbacks: matrix dominate fatiguing, compressive strength, electrical and thermal conductivity. It is believed that these characteristic can be improved upon with functionalized carbon nanotubes.

The main effort of this investigation is to improve the matrix dominate fatigue life. Under fatigue loading the final failure will be a result of either complete fiber fracture (fiber dominate) or buckling (matrix dominate). In woven carbon fiber reinforced polymers, CFRP, a number of damage modes occur before this final failure. Previous investigations have shown debonding of fiber-matrix interface, fiber breakage, normal and longitudinal matrix cracking under tension-tension and tension-compression loading.

It has been hypothesized that the molecular interactions between carbon nanotubes and polymer chains are stronger than the polymer chain to chain

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interactions. Carbon nanotubes may hinder fiber-matrix debonding as well as toughening the matrix, particularly under tension-compression loading.

2. Materials and Methods

2.1 Composite Fabrication

The carbon fiber epoxy composites were fabricated using the double bag vacuum assisted resin transfer molding method, or VARTM. Twelve ply of IM7 four harness satin weave carbon fibers and Epon 862 with curing W constitute the composite. The woven fibers were oriented in a 0°/90° fashion. Figure 2 shows the particular lay up. The fibers were subjected to a minimum of 6 hours of vacuum pressure to remove trapped air. A mixture of Epon 862 and curing agent W (100g: 26.4g) was degassed in a vacuum oven for at least half an hour to remove micro-bubbles. The fiber lay up was maintained at 115°F-140°F with heating pads, and the elevated temperature of the resin was maintained throughout infusion. The resin flow through the fibers was manually controlled at ¼" per minute. The composite was then cured at 250°F for two hours, and post-cured at 350°F for two additional hours while under vacuum pressure.

The VARTM process is an art in and of itself. Essentially, every composite fabricated is a different material with its own properties. Throughout this investigation much effort is placed on relating the fiber volume fraction, V_f, to the mechanical properties. Such effort is necessary in order to characterize the material as a whole. The V_f of each fabricated composite was calculated in accordance to ASTM D3171-99.

2.2 Ultrasonic NDE

During fatiguing a small imperfection on the surface or internally will often result in a premature failure. Ultrasonic C-scans were performed on the composite panels to access the fabrication quality. Ultrasonic C-scans are just one of many forms of nondestructive evaluation. The panel is submerged in a bath of water, and a transducer sweeps over the entire panel blasting sound waves through the composite. As the sound waves propagate through the any imperfections in the epoxy absorb some of the energy of the sound waves. The strength of the signal that is reflected back, after passing through the composite is recorded as a colorful image. Panels with higher void content interpreted by C-scan had imperfections visible to the eye and fatigue life was shorter with greater scatter.

2.3 Specimen Specifications

ASTM standards currently give several specifications and methods tensile and fatigue testing. Preliminary specimen geometry research was performed to discover the best specimen specifications for different tests. The specimens for tensile tests were one-half inch wide and six to ten inches in length. It was concluded that short dog bone shaped specimen with forty-five degree angled tabs worked well for tension-compression; where as, straight specimen with one-half inch wide by six inch specimen and seven to ten degree angled tabs worked well in tension-tension fatiguing.

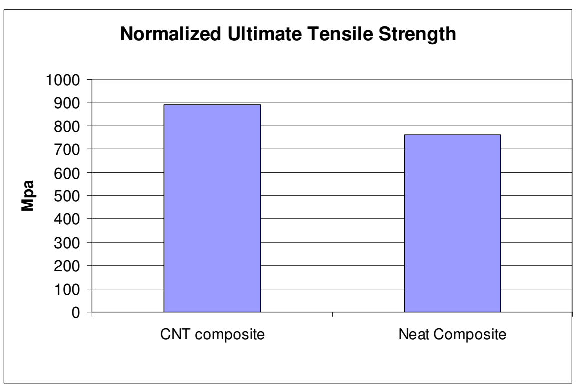
3. Static & Fatigue Results

3.1 Quasi-Static Testing

Composites fabricated using the VARTM process will have unique properties, because it is impossible to control the exact fiber to epoxy ratio. In an effort to characterize IM7 carbon fiber epoxy composites it is necessary to normalize all results so that all for any volume fraction roughly the same ultimate tensile strength will be reported. Composites were fabricated at two different volume fractions; 52% and 64%. The ultimate tensile strength for the panels averaged to be 681 Mpa and 802 Mpa, respectively; thirteen tests were performed. From this the following normalization curve was developed so that the UTS would be normalized to a value of 761 Mpa (the value expected for a volume fraction of 60%).

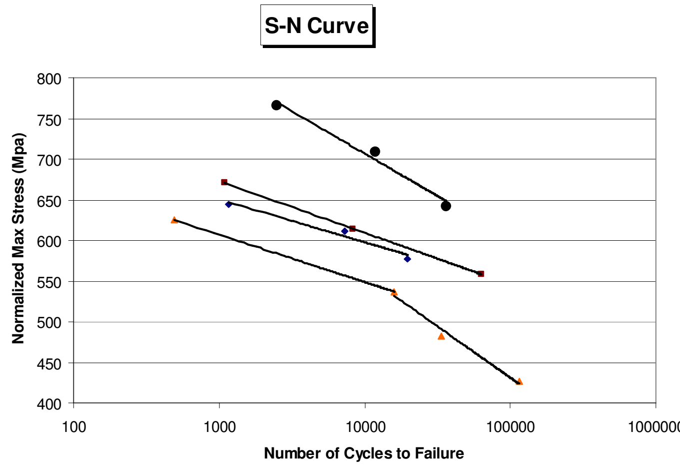
$$\sigma_{Normalized} = \frac{60\%}{Fiber\ Volume\ Fraction}(\sigma - 162.5) + 162.5$$

The following graph shows the normalized values for the neat composite and for the CNT composite. A 17% increase in ultimate tensile strength was seen.



3.2 Cyclic Testing

Fatigue test were run at a frequency of five hertz and an R-ratio(minimum load over maximum load) of 0.1 and -0.1. The specimen was loaded slowly (250N/sec) to the mean load where sinusoidal cyclic loading took over. The specimens were fatigued to final failure.



The above curve is a standard semi-log S-N curve. As evident from the curve CNTs improved the fatigue life of the composite. Interestingly enough, a bi-linear curve was discovered for tension-compression cyclic loading at lower R-ratios, because the specimen will fail either by fiber fracture or buckling.

4. Microscopy

Failed specimens were analyzed under optical microscope. The damage mechanisms interpreted from microscopy for tension-tension fatiguing started with transverse cracking of the matrix. These cracks propagate to the longitudinal fibers (parrellel to load) where they become longitudinal cracks. As these cracks grow the load is constantly redistributed throughout the specimen. At some point one of the fibers becomes overloaded, this trend continues until final failure. Tension-compression fatiguing starts off the same, but as longitudinal cracks form the turn into major delaminations due to Poisson's effect. Test run on the first half of the bi-linear s-n curve and lower cycles of the second half will result in a mixed-mode damage. That is the specimen is experiencing both fiber fracture and major delaminations. See appendix for image

Conclusion

It was determined that a small change in the void content will not affect static tensile properties. This may be because the strength of the matrix plays a small role in the ultimate tensile strength of the composite. However, voids will shorten the fatigue life of composites, because they may present a location for major cracks to start. Tension-tension fatigue failure is ultimately a result of fiber breakage. Tension-compression fatigue failure may result from either fiber breakage or, more likely, buckling. This mixed-mode of damage and final failure was discovered for tension-compression fatiguing at approximately R ratios of 0 to -0.4. A concept for a critical damage design curve was developed. The carbon nanotube investigations showed improvements in the ultimate tensile strength and in the tension-tension fatigue life on the order of 15 to 20 percent.

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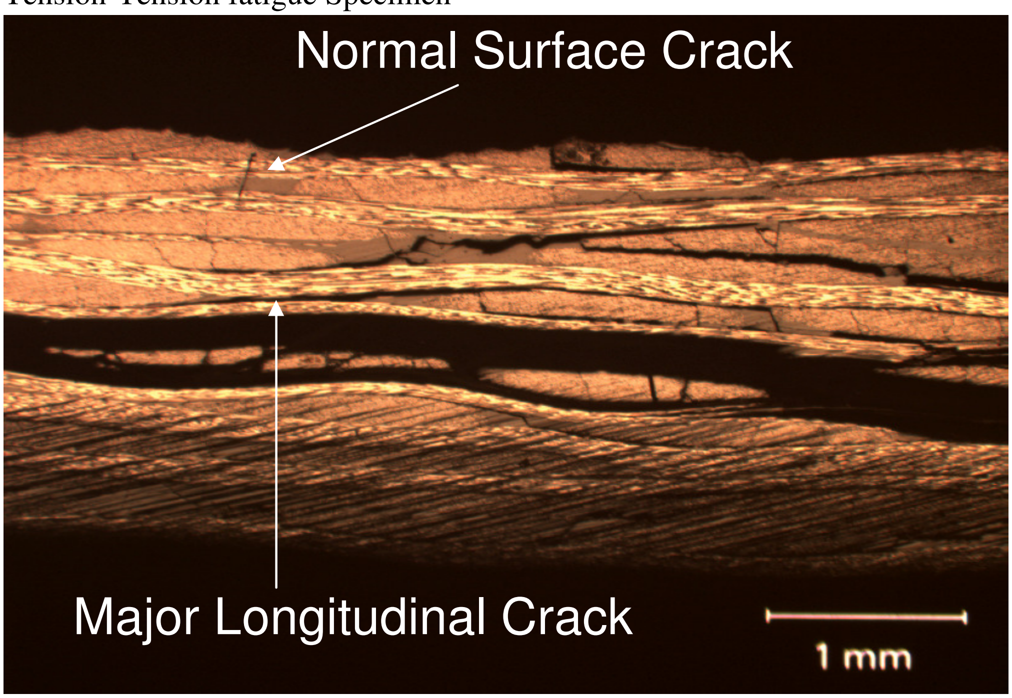
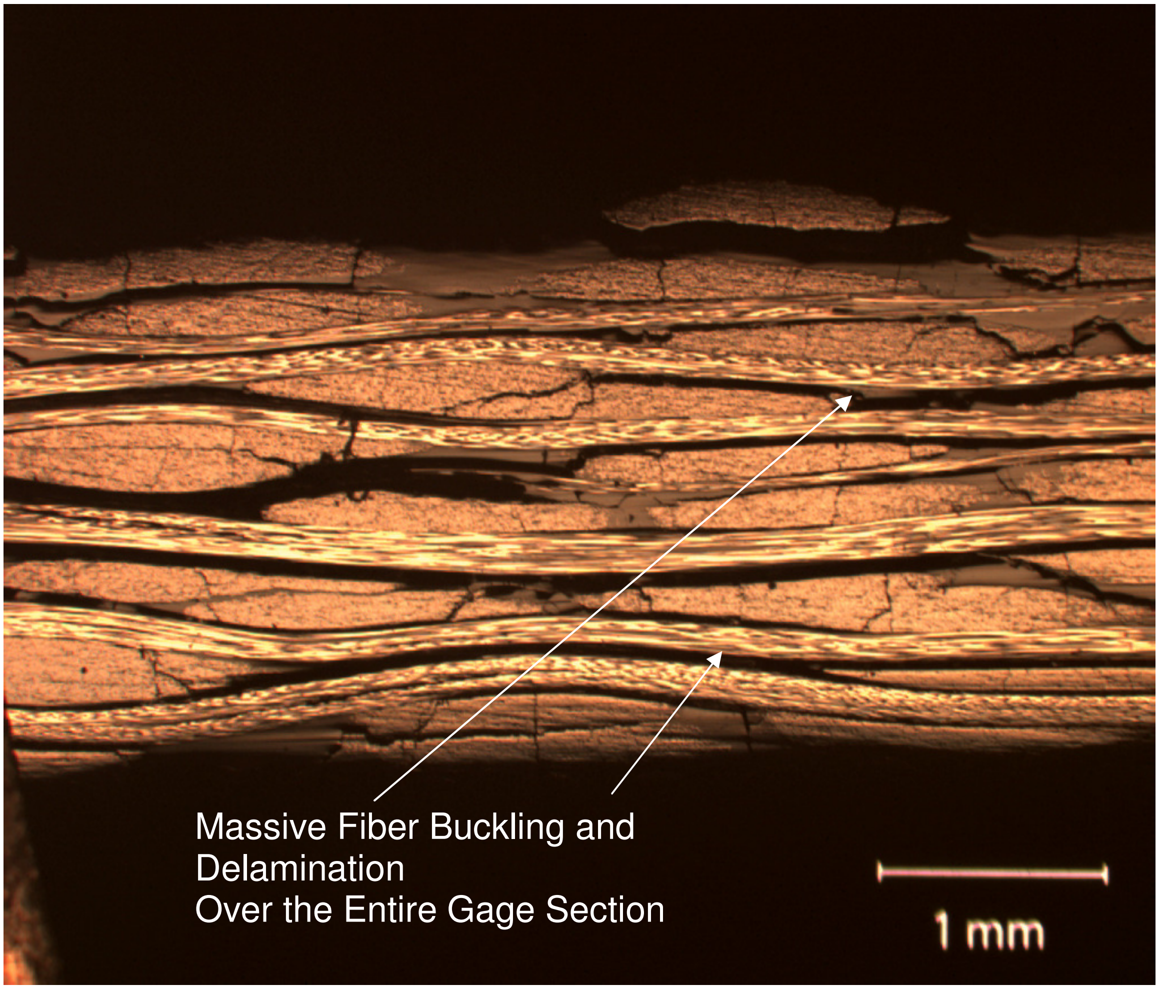
Appendix

Tension-Tension fatigue Specimen





Tension-Compression fatigue Specimen